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Elastic scattering and the current-voltage characteristics of superconducting Nb-InAs-Nb junctions

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Superconducting niobium contacts are attached to a 0.8-μm-long epitaxially grown InAs channel sandwiched between insulating InGaAs layers. The current-voltage characteristics show nonlinearities at submultiples of the superconducting energy gap indicative of multiple-Andreev reflections. We demonstrate that an increase in the elastic scattering rate in the InAs channel, caused by Ar-ion etching, diminishes the order of Andreev reflections and explains the overall shape of the current-voltage characteristics.

Semiconductor-coupled superconductors (SSmS) are increasingly being studied as a step towards a superconducting transistor. Most recent work concentrates on using a two-dimensional electron gas between superconducting electrodes.[1,2] The high mobility obtainable in epitaxially grown semiconducting heterostructures may provide a substantial supercurrent which can be controlled by varying the carrier concentration with a gate. Technological progress has been slow, but promising results have been obtained by using superconducting niobium with an InAs quantum well.[1] The conceptual understanding of semiconductor coupled superconductors has advanced as well. In particular, the voltage carrying state is increasingly being understood as a result of a nonequilibrium energy distribution of carriers generated by elastic and Andreev scattering at the interfaces between the superconductor and the semiconductor.[3] In practice, in most devices elastic scattering in the semiconductor is unavoidable. In this letter we report on a study of the influence of elastic scattering on the current-voltage characteristics in Nb-InAs-Nb junctions.

The structure of the SSmS sample is shown schematically in Fig. 1. The length L of the InAs semiconductor channel is defined lithographically and is 0.8 μm. The width of the contact is 35 μm. The insulating InAlAs/InGaAs top layers are optimized to make the resistance of the InAs channel as low as possible.[4] In order to introduce elastic scattering in the channel, a technique is used in which the top layers are slowly removed, thus deliberately deteriorating the optimized channel properties like carrier concentration and mobility. This can be done by 10-W Ar rf sputter cleaning, which is normally used to clean or etch samples before metallization. When the carrier concentration and mobility are reduced, the elastic scattering length decreases. After etching, a current-voltage measurement is done at low temperature (1.9 K). This cycle can be repeated several times.

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In Figs. 2(a) and 2(b) the conductance dI/dV vs V for a typical sample is shown. The curve labeled 0-minute represents the conductance of the sample before any etching has taken place. The conductance of this sample is high at applied voltages lower than the superconducting gap Δ of niobium, due to a high probability of Andreev reflection at the SSm barriers. An electron in Sm approaching the SSm barrier faces the superconducting gap which is forbidden for electrons, and a hole is reflected so that two coupled electrons (Cooper pair) can enter the superconductor. The arrows indicate the effects of multiple Andreev reflections leading to conductance changes at submultiples of the superconducting energy gap.[5]

Hall measurements on this sample give an elastic scattering length of 2.1 μm. Since this is much more than the channel length of 0.8 μm elastic scattering can be neglected. Also, the calculated resistance of the semiconductor $R_{Sm}=0.8\ \Omega$ is much smaller than the measured normal resistance $R_n=7.5\ \Omega$. This indicates that the voltage drop is mostly over the SSm barriers, and $R_n=R_{Sm}+2R_{bar}$. In the present sample no supercurrent is observed because of

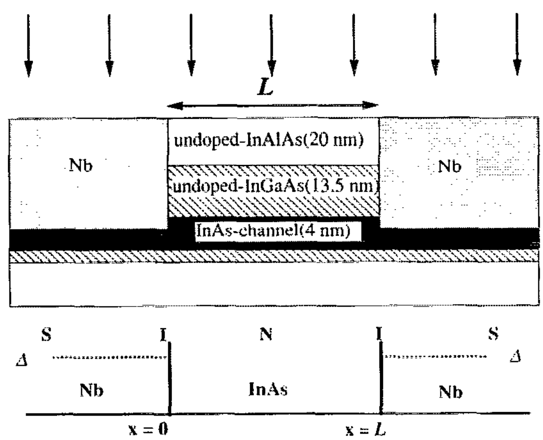

FIG. 1. Schematic structure of the sample. The current path is via the InAs channel. Etching takes place at the top layers. Inset: Schematic structure of the sample as used in the OTBK theory.

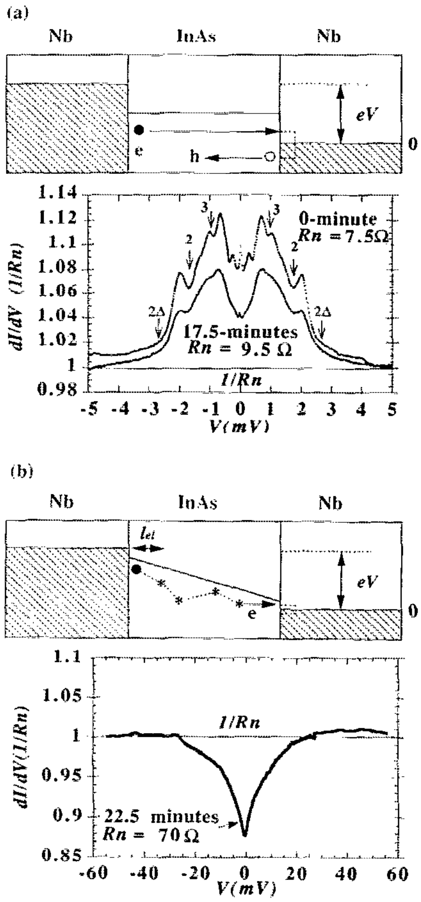

FIG. 2. Conductance characteristics of the variously etched sample. The conductance is expressed in units of the inverse of the normal state resistance R_n. Etching introduces more elastic scattering in the InAs channel. Measurement temperature is 1.9 K. (a) In the 0 and 17.5 min etching samples, elastic scattering at the Nb-InAs barriers is prevalent. The samples show multiple Andreev reflection peaks at submultiples of the superconducting gap Δ (arrows). For all voltages, the conductance is higher than $1/R_n$ (excess current). (b) After 22.5 min of etching, elastic scattering in the InAs is prevalent. The sample does not show multiple Andreev reflection. For all voltages, the conductance is lower than $1/R_n$ (current deficit).

the barrier resistance $R_{\rm bar}$. The critical temperature T_c of the niobium electrodes is 9.0 K.

After 17.5 min of etching the resistance has increased to 9.5 Ω. The multiple Andreev reflections are still visible but smeared. After another 5 min of etching the dI/dV characteristics have changed dramatically [Fig. 2(b)]. R_n was increased to 70 Ω, the multiple Andreev reflections had disappeared completely and the dI/dV curve is entirely below the $1/R_n$ line, in contrast to Fig. 2(a). The T_c of the sample has not changed, indicating that the etching does not effect the niobium electrodes. Note that because of the large semiconductor resistance $R_{\rm Sm}$ the superconducting gap is visible at much higher voltages than in Fig. 2(a). So only at applied voltages of about 20 mV the voltage drop over the interfaces is equal to the superconducting gap. This way, we can make a calculation of the elastic mean free path $l_{\rm el}$ and $R_{\rm Sm}$ in the 22.5-min sample. This calculation yields $l_{\rm el}=60$ nm$\ll L$ and $R_{\rm Sm}=62\ \Omega \gg R_{\rm bar}$, with $R_{\rm bar}$ the SSm barrier resistance. So in the 22.5 min sample elastic scattering in the semiconductor is prevalent. The difference between 17.5 and 22.5 min of etching is so drastic because in the latter sample the InAlAs support layer is completely removed.

Subharmonic gap structure as observed in Fig. 2(a) is currently understood as due to multiple Andreev reflections. At a normal metal-superconductor interface electrons at energy E above the Fermi level are scattered into holes at energy $-E$ and a Cooper pair is formed in the superconductor. If a normal metal is sandwiched between two superconductors this process may occur several times, leading to structures in the conductance of the sample at bias voltages $2\Delta/n$, with Δ the superconducting energy gap (n is an integer). Octavio, Tinkham, Blonder, and Klapwijk[6] (OTBK) describe a SNS structure (N being a normal metal) with elastic scattering lumped at the SN interfaces, represented by a delta-function potential of variable height Z. In this so-called (SINIS) structure [see the inset of Fig. (1)], where I represents the barrier at the interface, it is further assumed that inelastic scattering is absent in the normal region N between the interfaces. This implies that the energy distribution functions of carriers in N are position independent and reflect only the acceleration due to the applied voltage V. Unfortunately, in the OTBK model the influence of elastic scattering has not been analyzed.

In the theory, the quasiparticles in N are separated into two subpopulations, depending on the direction of motion, $f_{\rightarrow}(E,x)$ and $f_{\leftarrow}(E,x)$, which differ from the equilibrium Fermi function $f_0(E)$. The energy E is measured with respect to the local chemical potential. Electrons injected at $x=0$ with energy E arrive at the superconductor at $x=L$ with energy $E+eV$ and we can write

$$f_{\rightleftarrows}(E,L)=f_{\leftrightarrows}(E-eV,0), \tag{1}$$

$f_{\rightarrow}(E)$ is determined by $f_{\rightarrow}$ and f_0, together with the reflection and transmission coefficients $A(E)$, $B(E)$ and $T(E)$, the probability of Andreev reflection, normal reflection and transmission, respectively. This problem can be solved self-consistently, and the total current at a particular position x is found by integrating over the difference in the distributions.

$$I=2N(0)ev_FS\int dE[f_{\rightarrow}(E)-f_{\leftarrow}(E)] \tag{2}$$

with $N(0)$ the normal metal single spin density of states at the Fermi level, v_F the Fermi velocity, and S the current carrying area.

As stated, one of the assumptions of the theory is that all scattering in the SSmS junction is elastic and takes place at the SSm barriers (the Sm is metallic at low temperatures, so we can replace Sm by N). This assumption is necessary because if a carrier would scatter at a different place than the SSm barriers, no exact predictions can be made about the probability that a carrier will reach the other SSm barrier. In other words: The assumption which has to be made, is that the SSm barrier resistance $R_{\rm bar}$ is much higher than $R_{\rm Sm}$.

In the original 0-minute sample $R_{bar}/R_{Sm} \approx 7$ and the OTBK assumption is met. When elastic scattering is introduced in the InAs semiconductor by Ar-ion etching this ratio changes to $R_{bar}/R_{Sm} \approx 0.1$ for the 22.5 minutes etching sample. With decreasing elastic scattering length, the probability that an electron or hole reaches the second SSm barrier after having crossed the first decreases. By reducing the probability that a carrier crosses the semiconductor, elastic scattering in the semiconductor effectively reduces the probability of multiple Andreev reflection. The populations at $x=0$ and $x=L$ are no longer identical, hence Eq. (1) is violated. This may be qualitatively described in terms of an increased barrier height Z due to elastic scattering. Flensberg *et al.*[7] have explicitly calculated the influence of an increasing barrier height Z on the current-voltage characteristics. By increasing Z slightly, they show that the higher order peaks due to multiple Andreev reflection disappear. By increasing Z strongly, the peaks in the dI/dV vs V characteristics are found to disappear completely while a current deficit develops. This is exactly what we observe in our measurements.

It should be stressed that in the present work the increase in SSm barrier height Z is entirely due to elastic scattering in the semiconductor and not to deliberate changing of the barrier as in recent work by Kleinssasser.[8]

To use a SSmS junction as a superconducting transistor, it is necessary to have high supercurrents. In a recent theory for the current transport in SSmS junctions, it is stated that the fundamental mechanism for the flow of supercurrent is a bound state of multiple Andreev reflections.[9] In this letter it is shown that a large elastic scattering length is necessary to observe multiple Andreev reflection. The flow of supercurrent as well as the finite voltage state on the current-voltage characteristics depend on the elastic scattering length, so the elastic scattering length is an important parameter to design a superconducting transistor.

In summary, we studied the influence of elastic scattering on the current-voltage characteristics of superconducting Nb-InAs-Nb junctions. Elastic scattering is introduced by etching of the junction's surface layers. The elastic scattering results in a drastic decrease in Andreev reflection. This can be modeled by an apparent increase in Nb-InAs barrier height.

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